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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project studied individual search behavior and coordination of large groups of individual agents, and how consensus is achieved in decision-making. Animal groups frequently display highly coordinated movements, and provide an excellent vehicle by which to understand general principles that underlie collective behavior. We studied collective movement in animal populations, and the relationship between individual decision rules and emergent collective patterns, especially when different individuals have conflicting information. We expanded classical search models, extending multi-armed bandit and other Bayesian approaches to information gathering

15. SUBJECT TERMS

collective motion, collective decision making, information transfer, consensus, search algorithms

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a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Simon Levin
UU	UU	UU			19b. TELEPHONE NUMBER 609-258-6880

Report Title

ARO Final Report: Coordination and Collective Decision Making W911NG-11–1–0385

ABSTRACT

This project studied individual search behavior and coordination of large groups of individual agents, and how consensus is achieved in decision-making. Animal groups frequently display highly coordinated movements, and provide an excellent vehicle by which to understand general principles that underlie collective behavior. We studied collective movement in animal populations, and the relationship between individual decision rules and emergent collective patterns, especially when different individuals have conflicting information. We expanded classical search models, extending multi-armed bandit and other Bayesian approaches to information gathering. We investigated the role of communication topology in generic models of group motion and decision-making, with particular reference to optimizing performance metrics such as speed, accuracy and robustness of decisions to intrinsic or extrinsic sources of error. Central was the degree to which collective optimization can be approximated in situations where individuals operate for individual benefit rather than group success. We employ a comprehensive approach using mathematical models of collective foraging (self-propelled interacting particles) within an evolutionary framework, and tools from dynamical systems theory, statistical mechanics, adaptive dynamics and state-of-the-art computational hardware and algorithms. We used large-scale individual-based simulation and mathematical analysis under biologically realistic assumptions, yet the results can help us elucidate fundamental biological principles that can be relevant to a wide range of scales and species from social bacteria to large mammals.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

04/24/2014 51.00 Paul Reverdy, Vaibhav Srivastava, Naomi Ehrich Leonard. Modeling human decision-making in generalized Gaussian multi-armed bandits,
Proceedings of the IEEE, (04 2014): 544. doi:

04/24/2014 52.00 Vaibhav Srivastava, Naomi Ehrich Leonard. Collective decision-making in ideal networks: The speed-accuracy tradeoff,
IEEE Transactions on Control of Network Systems, (03 2014): 121. doi:

07/31/2012 1.00 A. C. Gallup, A. Chong, I. D. Couzin. The directional flow of visual information transfer between pedestrians,
Biology Letters, (03 2012): 0. doi: 10.1098/rsbl.2012.0160

07/31/2012 7.00 J. J. Hale, A. C. Gallup, D. J. T. Sumpter, S. Garnier, A. Kacelnik, J. R. Krebs, I. D. Couzin. Visual attention and the acquisition of information in human crowds,
Proceedings of the National Academy of Sciences, (04 2012): 0. doi: 10.1073/pnas.1116141109

07/31/2012 2.00 N. E. Leonard, T. Shen, B. Nabet, L. Scardovi, I. D. Couzin, S. A. Levin. Decision versus compromise for animal groups in motion,
Proceedings of the National Academy of Sciences, (12 2011): 0. doi: 10.1073/pnas.1118318108

08/01/2012 8.00 Sepideh Bazazi, Frederic Bartumeus, Joseph J. Hale, Iain D. Couzin, John M. Fryxell. Intermittent Motion in Desert Locusts: Behavioural Complexity in Simple Environments,
PLoS Computational Biology, (5 2012): 0. doi: 10.1371/journal.pcbi.1002498

08/01/2012 9.00 Nils Olav Handegard, Kevin M. Boswell, Christos C. Ioannou, Simon P. Leblanc, Dag B. Tjøstheim, Iain D. Couzin. The Dynamics of Coordinated Group Hunting and Collective Information Transfer among Schooling Prey,
Current Biology, (7 2012): 0. doi: 10.1016/j.cub.2012.04.050

08/01/2013 29.00 Allison Kolpas, Michael Busch, Hong Li, Iain D. Couzin, Linda Petzold, Jeff Moehlis. How the Spatial Position of Individuals Affects Their Influence on Swarms: A Numerical Comparison of Two Popular Swarm Dynamics Models,
PLoS ONE, (03 2013): 58525. doi:

08/01/2013 42.00 Ugo Lopez, Jacques Gautrais, Iain D. Couzin, Guy Theraulaz. From behavioral analyses to models of collective motion in fish schools. ,
Interface Focus, (12 2012): 693. doi:

08/01/2013 40.00 Ioannis Poulakakis, Luca Scardovi, Naomi E. Leonard. Node classification in collective evidence accumulation toward a decision,
Proceeedings of the 51st IEEE Conference on Decision and Control, (12 2012): 4648. doi:

08/01/2013 39.00 Darren Pais, Carlos H. Caicedo-Nunez, Naomi E. Leonard. Hopf bifurcations and limit cycles in evolutionary network dynamics.,
SIAM J on Applied Dynamical Systems, (12 2012): 1754. doi:

08/01/2013 38.00 Simon Garnier, Tucker Murphy, Matthew Lutz, Edward Hurme, Simon Leblanc, Iain D. Couzin. Stability and responsiveness in a self-organizing living architecture,
PLoS Computational Biology, (03 2013): 1002984. doi:

08/01/2013 37.00 Kolbjorn Tunstrom, Yael Katz, Christos C. Ioannou, Cristian Huepe, Matthew J. Lutz, Iain D. Couzin. Collective states, multistability and transitional behavior in animal groups,
PLoS Computational Biology, (02 2013): 1002915. doi:

08/01/2013 36.00 George F. Young, Luca Scardovi, Andrew Cavagna, Irene Giardina, Naomi E. Leonard. Starling Flock Networks Manage Uncertainty inConsensus at Low Cost,
PLoS Computational Biology, (01 2013): 1002894. doi:

08/12/2015 67.00 Andrew Berdahl, Colin J. Torney, Emmanuel Schertzer, Simon A. Levin. On the evolutionary interplay between dispersal and local adaptation in heterogeneous environments,
Evolution, (06 2015): 1390. doi:

08/12/2015 76.00 Colin J. Torney, Tommaso Lorenzi, Iain D. Couzin, Simon A. Levin. Information processing and the evolution of unresponsiveness in collective systems,
Journal of the Royal Society Interface, (08 2015): 20140893. doi:

08/12/2015 75.00 Hans A. Hofmann, Annaliese K. Beery, Daniel T. Blumstein, Iain D. Couzin, Ryan L. Earley, Loren D. Hayes, Peter L. Hurd,, Eileen A. Lacey, Steven M. Phelps, Nancy G. Solomon, Michael Taborsky, Larry J. Young, Dustin R. Rubenstein. An evolutionary framework for studying mechanisms of social behavior,
Trends in Ecology & Evolution, (10 2014): 581. doi:

08/12/2015 73.00 Ariana Strandburg-Peshkin, Damien R. Farine, Iain D. Couzin, Margaret C. Crofoot. Shared decision-making drives collective movement in wild baboons,
Science, (06 2015): 1358. doi:

08/12/2015 72.00 Daniel T. Swain, Iain D. Couzin, Naomi Ehrich Leonard. Coordinated Speed Oscillations in Schooling Killifish Enrich Social Communication,
Journal of Nonlinear Science, (07 2015): 0. doi:

08/12/2015 70.00 Sara Brin Rosenthal, Colin R. Twomey, Andrew T. Hartnett, Hai Shan Wu, Iain D. Couzin. Revealing the hidden networks of interaction in mobile animal groups allows prediction of complex behavioral contagion,
PNAS, (04 2015): 4690. doi:

08/12/2015 69.00 Naomi Ehrich Leonard, Alex Olshevsky. Cooperative learning in multiagent systems from intermittent measurements,
SIAM J of Control and Optimization, (06 2015): 1. doi:

08/12/2015 68.00 Christos C. Ioannou, Manvir Singh, Iain D. Couzin. Potential Leaders Trade Off Goal-Oriented and SociallyOriented Behavior in Mobile Animal Groups,
The American Naturalist, (08 2015): 284. doi:

08/19/2015 85.00 Naomi Ehrich Leonard. Multi-Agent System Dynamics: Bifurcation and Behavior of Animal Groups,
IFAC Annual Reviews in Control, (09 2014): 171. doi:

08/26/2014 56.00 Andrew Berdahl, Peter A H Westley, Simon A Levin, Iain D Couzin, Thomas P Quinn. A collective navigation hypothesis for homeward migration in anadromous salmonids,
Fish and Fisheries, (06 2014): 1. doi: 10.1111/faf.12084

08/26/2014 57.00 L. Giuggioli, J. R. Potts, D. I. Rubenstein, S. A. Levin. Stigmergy, collective actions, and animal social spacing,
Proceedings of the National Academy of Sciences, (09 2013): 1. doi: 10.1073/pnas.1307071110

08/26/2014 58.00 Albert B. Kao, Iain D. Couzin. Decision accuracy in complexenvironments is often maximizedby small group sizes,
Proceedings of the Royal Society B, (04 2014): 20133305. doi:

08/26/2014 61.00 Andrew C. Gallup, Andrew Chong, Alex Kacelnik, John R. Krebs, Iain D. Couzin. The influence of emotional facial expressions on gaze-following in grouped and solitary pedestrians,
Scientific Reports, (07 2014): 5794. doi: 10.1038/srep05794

08/26/2014 62.00 Albert B. Kao, Noam Miller, Colin Torney, Andrew Hartnett, Iain D. Couzin. Collective learning and optimal consensus decisions in social animal groups,
PLoS Computational Biology, (08 2014): 1. doi: 10.1371/journal.pcbi.1003762

09/24/2012 18.00 Vishwesha Guttal, Pawel Romanczuk, Stephen J. Simpson, Gregory A. Sword, Iain D. Couzin, Andrew Liebhold. Cannibalism can drive the evolution of behavioural phase polyphenism in locusts,
Ecology Letters, (10 2012): 1158. doi: 10.1111/j.1461-0248.2012.01840.x

09/24/2012 19.00 C.C. Ioannou, V. Guttal, I.D. Couzin. Predatory fish select for coordinated collective motion in virtual prey,
Science, (09 2012): 1212. doi:

10/15/2012 20.00 Ugo Lopez, Jacques Gautrais, Iain D. Couzin, Guy Theraulaz. From behavioral analyses to models of collective motion in fish schools,
Interface Focus, (10 2012): 1. doi:

TOTAL: **43**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Iain Couzin

2014

The Kwanghil Koh Lecture on Mathematics in Our Time, College of Sciences, NC State University

Plenary Speaker, Max Planck International Research School in Organismal Biology, Grand Challenges Symposium, Konstanz, Germany

Plenary Speaker, The Joint Annual Meeting of the Society of Mathematical Biology and the Japanese Society for Mathematical Biology, Osaka, Japan

Keynote Address, 13th International Conference on Autonomous Agents and Multiagent Systems, Paris, France

The Institute of Science and Technology (IST) Distinguished Lecturer Series, Austria

Interdisciplinary Distinguished Seminar, Federal Laboratory for Analytical Sciences and the Army Research Office, NC, USA

Public Lecture and Keynote, Courant Research Center Symposium "Evolution of Social Behavior," University of Göttingen, Germany

Plenary Speaker, Interaction Networks and Collective Motion in Swarms, Flocks and Crowds, Helsinki, Finland

Plenary Speaker, Animal Behavior Society Meeting, Princeton, USA

2015

The Directors Seminar, Howard Hughes Medical Institute, Janelia Research Campus, USA

Plenary Lecture, Physics of Emergent Behavior: From Molecules to Planets, London Science Museum

Plenary Lecture. Animal Social Networks in Behavioral Research, University of Neuchâtel, Switzerland

Naomi Leonard

2014

Invited lecture Radcliffe Institute Workshop on Swarm Behavior, Cambridge, MA, 2014

Invited lecture, Workshop on Modeling and Control of Social Networks, Rutgers, Camden, 2014

Invited Keynote, IFAC World Congress, Cape Town, South Africa, 2014

2015

Invited talk, Control of Nonlinear Physical Systems Workshop, American Control Conference

Panel on Biocomplexity, DARPA Workshop, New York City

Invited lecture, Ecology and Evolutionary Biology Department Colloquium, Princeton University

Invited lecture, Networks Seminar, University of Houston

Invited lecture, ExxonMobil Research, Houston TX

Simon A. Levin

2014

Bringing Theory to Real-World Systems," Nurturing Ideas and Scientists in Ecology: Symposium in Honor of Bill Robertson, ESA Annual Conference, Sacramento, CA (August)

"Microscopic Processes and Macroscopic Patterns" (with Juan Bonachela, University of Strathclyde, Scotland), Crest International Workshop: Advances in the Plankton Ecosystem Model and the Evaluation of Biodiversity, Tokyo University of Marine Science and Technology, Shinagawa Campus (October)

Plenary Lecture, "Critical Transitions in Space and Time," Spatio-Temporal Dynamics in Ecology Workshop, Lorentz Center, University of Amsterdam, The Netherlands (December)

Plenary Lecture, "Critical Transitions in Space and Time," Workshop on Mathematical Biology and Nonlinear Analysis, University of Miami, Coral Gables, FL (December)

2015

"Validation and the Problem of Relevant Detail," Validation: What Is It? Conference, University of California, Institute for Mathematical and Behavioral Sciences, University of California, Irvine (February)

"Dealing with Public Goods and Common Pool Resources," IMBS Colloquium, University of California, Irvine (February)

"Collective Motion, Collective Decision-Making, and Collective Action: From Microbes to Societies," MASpread/Rapid Trade Meeting, University of Arizona, Tempe, AZ (March)

"Channeling Luca Pacioli: Multi-Disciplinarity and a Sustainable Future," Lecture Given on Receiving the Luca Pacioli Prize, Ca'Foscari University of Venice, Italy (March)

"Dealing with Public Goods and Common Pool Resources," The IGB Colloquium, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany (March)

Keynote Lecture. "Collective Motion, Collective Decision-Making and Collective Action: From Microbes to Societies." Deutsche Physikalische Gesellschaft Spring Meeting. Physics of Socio-Economic Systems Division, Berlin, Germany (March)

"Evolutionary Perspectives on Strategy," Business Strategy Interfaces and Frontiers, PRISM Foundation, New York, NY (May)

"Cooperation in the Global Commons," NetSci – International School and Conference on Complex Networks, La Herradura, Spain (June)

Number of Presentations: 32.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

TOTAL:

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

04/24/2014 53.00   Vaibhav Srivastava, Paul Reverdy, Naomi E. Leonard. On optimal foraging and multi-armed bandits,
51st Annual Allerton Conference on Communication, Control and Computing. 02-OCT-13, . : ,

04/24/2014 54.00   Vaibhav Srivastava, Naomi E. Leonard. On the speed-accuracy trade-off in collective decision making,
Proceedings of the 52nd IEEE Conference on Decision and Control, Florence Italy. 10-DEC-13, . : ,

04/24/2014 55.00   Naomi Ehrich Leonard, Alex Olshevsky. Cooperative learning in multi-agent systems from intermittent
measurements,
52nd IEEE Conference on Decision and Control, Florence, Italy. 10-DEC-13, . : ,

08/18/2015 82.00   Paul Reverdy, Naomi E. Leonard. Satisficing in Gaussian bandit problems,
53rd IEEE Conference on Decision and Control, Los Angeles, CA. , . : ,

08/18/2015 84.00   Naomi Ehrich Leonard. Multi-Agent System Dynamics: Bifurcation and Behavior of Animal Groups,
IFAC Symposium on Nonlinear Control Systems (NOLCOS), Toulouse, France. , . : ,

08/18/2015 83.00   William Scott, Naomi Ehrich Leonard. Dynamics of Pursuit and Evasion in a Heterogeneous Herd,
53rd IEEE Conference on Decision and Control, Los Angeles, CA. , . : ,

08/19/2015 86.00   Vaibhav Srivastava, Paul Reverdy, Naomi E. Leonard. Surveillance in an Abruptly Changing World via
Multiarmed Bandits,
53rd IEEE Conference on Decision and Control, Los Angeles, CA. , . : ,

08/26/2014 59.00   Paul Reverdy, Vaibhav Srivastava, Naomi E. Leonard. Algorithmic models of human decision making in
Gaussian multi-armed bandit problems,
2014 European Control Conference (EEC). 24-JUN-14, . : ,

TOTAL: **8**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper

02/18/2013 24.00 Darren Pais, Naomi E. Leonard. Adaptive Network Dynamics andEvolution of Leadership in Collective Migration,
Physica D: Nonlinear Phenomena (11 2012)

03/12/2013 25.00 Ariana Strandburg-Peshkin, Colin R. Twomey, Nikolai W. Bode, Albert B. Kao, Yael Katz, Christos C. Ioannou, Brin Rosenthal, Colin J. Torney, Haishan Wu, Simon A. Levin, Iain D. Couzin. Visual sensory networks and effectiveinformation transfer in animal groups,
PNAS (01 2013)

03/12/2013 27.00 Albert B. Kao, Noam Miller, Colin Torney, Andrew T. Hartnett, Iain D. Couzin. Collective learning and optimal consensus decisions in social animal groups,
PNAS (02 2013)

03/13/2013 28.00 Allison Kolpas, Michael Busch, Hong Li, Iain D. Couzin, Linda Petzold, Jeff Moehlis. How the spatial position of individuals affects their influence on swarms: A numerical comparison of two popular swarm dynamics models,
PLoS ONE (11 2012)

07/31/2012 6.00 Darren Pais, Carlos H. Caidedo-Nunez, Naomi E. Leonard. Hopf bifurcations and limit cycles in evolutionary network dynamics,
SIAM J on Applied Dynamical Systems (05 2012)

07/31/2012 5.00 Ioannis Poulakakis, Luca Scardovi, Naomi E. Leonard. Node classification in collective evidence accumulation toward a decision,
Proceedings of the 51st IEEE Conference on Decision and Control (03 2012)

07/31/2012 3.00 George F. Young, Luca Scardovi, Andrea Cavagna , Irene Giardina, Naomi E. Leonard. Starling flock networks manage uncertainty in consensus at low cost,
PLoS Computational Biology (07 2012)

08/01/2012 10.00 Allison K. Shaw, Iain D. Couzin. The evolution of movement behavior and information usage in seasonal environments,
The American Naturalist (07 2012)

08/01/2012 11.00 Kolbjorn Tunstrom, Yael Katz, Christos C. Ioannou, Cristian Huepe, Matthew J. Lutz, Iain D. Couzin. Collective states, multistability and transitional behavior in animal groups,
PLoS Computational Biology (06 2012)

08/01/2013 30.00 Katherine Fitch, Naomi Ehrich Leonard. Information Centrality and Optimal Leader Selection in Noisy Networks,
Proceedings of the IEEE Conference on Decision and Control (03 2013)

08/01/2013 35.00 Christos Ioannou, Manvir Singh, Iain Couzin. Potential leaders trade-off group cohesion for speed and accuracy in fish schools ,
Proceedings of the Royal Society B: Biological Sciences (06 2013)

08/01/2013 34.00 Ariana Strandburg-Peshkin, Colin R. Twomey, Nikolai W. Bode, Albert B. Kao, Yael Katz, Christos C. Ioannou, Brin Rosenthal, Colin J. Torney, Haishan Wu, Simon A. Levin, Iain D. Couzin . Visual sensory networks and effective information transfer in animal groups,
Current Biology (05 2013)

08/01/2013 33.00 Alfonso Perez-Escudero, Noam Miller, Andrew T. Hartnett, Simon Garnier, Iain D. Couzin, Gonzalo G. De Polavieja. Estimation models describe well collective decisions among three options, PNAS (05 2013)

08/01/2013 32.00 Vaibhav Srivastava, Naomi E. Leonard. On the Speed-Accuracy Trade-off in Collective Decision Making, Proceedings of the IEEE Conference on Decision and Control (11 2013)

08/01/2013 31.00 Vaibhav Srivastava, Paul Reverdy, Naomi E. Leonard. On Optimal Foraging and Multi-armed Bandits, Proceedings of the 51st Allerton Conference on Communication, Control, and Computing (07 2013)

08/02/2012 12.00 Vishwesha Guttal, Pawel Romanczuk, Stephen J. SImpson, Gregory A. Sword, Iain D. Couzin. Cannibalism can drive the evolution of behavioral-phase polyphenism in locusts, Ecology Letters (04 2012)

08/02/2012 15.00 Simon Garnier, Tucker Murphy, Matthew Lutz, Edward Hurme, Simon Leblanc, Iain D. Couzin. Stability and responsiveness in a self-organizing living architecture, PLoS Computational Biology (07 2012)

08/02/2012 14.00 C.C. Ioannou, V. Guttal, I.D. Couzin. Predatory fish select for coordinated collective motion in virtual prey, Science (01 2012)

08/02/2012 13.00 Andrew Berdahl, Colin J. Torney, Christos C. Ioannou, Jolyon J. Faria, Iain D. Couzin. Emergent sensing of complex environments by social animal groups, Science (06 2012)

08/12/2015 71.00 Vaibhav Srivastava, Paul Reverdy, Naomi Ehrich Leonard. Correlated Multiarmed Bandit Problem: Bayesian Algorithms and Regret Analysis, Automatica (07 2015)

08/18/2015 78.00 Andrew T. Hartnett, Emmanuel Schertzer, Simon A. Levin, Iain D. Couzin. Heterogeneous Preference and Local Nonlinearity in Consensus Decision-Making, Physical Review Letters (06 2015)

08/18/2015 80.00 Ioannis Poulakakis , Luca Scardovi, Naomi Ehrich Leonard Fellow, George F. Young. Information Centrality and Ordering of Nodes forAccuracy in Noisy Decision-Making Networks, IEEE TRANSACTIONS ON Automatic Control (to appear March 2016) (10 2012)

08/18/2015 77.00 Andrew M. Hein, Sara Brin Rosenthal, George I. Hagstrom, Andrew Berdahl, Colin J. Torney, Iain D. Couzin. The evolution of distributed sensing and collective computation in animal populations, PNAS (07 2015)

08/18/2015 79.00 Andrew M. Hein [L], Simon A. Levin. Physical limits on bacterial navigation in dynamic environments, Physical Review Letters (07 2015)

08/21/2015 87.00 Katherine Fitch, Naomi Ehrich Leonard. Joint Centrality Distinguishes Optimal Leaders in Noisy Networks, Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy (07 2014)

08/26/2014 60.00 Colin J. Torney, Tommaso Lorenzi, Iain D. Couzin, Simon A. Levin. Information processing and the evolution of unresponsiveness in collective systems, Journal of the Royal Society Interface (07 2014)

08/26/2014 63.00 Katherine Fitch, Naomi E. Leonard. Joint centrality distinguishes optimal leaders in noisy networks, IEEE Transactions on Control of Network Systems (07 2014)

08/26/2014 64.00 George F. Young, Luca Scardovi, Naomi E. Leonard. A New Notion of Effective Resistance for DirectedGraphs—Part I: Definition and Properties, IEEE TRANSACTIONS ON Automatic Control (10 2013)

08/26/2014 65.00 George F. Young, Luca Scardovi, Naomi E. Leonard. A New Notion of Effective Resistance for DirectedGraphs—Part II: Computing Resistances, IEEE TRANSACTIONS ON Automatic Control (10 2013)

09/21/2012 16.00 Ugo Lopez, Jacques Gautrais, Iain D. Couzin, Guy Theraulaz. From behavioral analyses to models of collective motion in fish schools,
Interface Focus (06 2012)

09/21/2012 17.00 Naomi Ehrich Leonard, Alex Olshevsky. Cooperative learning in multi-agent systems from intermittent measurements,
SIAM J of Control and Optimization (09 2012)

TOTAL: **31**

Number of Manuscripts:

Books

Received   Book

TOTAL:

Received   Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Naomi Leonard

2014

Inaugural Glenn L. Martin Medal, A. James Clark School of Engineering, University of Maryland

Nyquist Lecture Award, Dynamic Systems and Control Division, ASME

Keynote Lecture, International Federation of Automatica Control (IFAC) World Congress, Cape Town, South Africa

Simon A. Levin

2014

Tyler Prize for Environmental Achievement

Luca Pacioli Prize, Ca'Foscari University of Venice, Italy

Foreign Member, Istituto Lombardo, Milan

IIASA Distinguished Visiting Fellow

Keynote Lecture, German Physical Society, Physics of Socio-Economic Systems Division

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Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Andrew M. Hein	0.08
George I. Hagstrom	0.80
Karla Kvaternik	1.00
Matthieu R. Barbier	0.20
FTE Equivalent:	**2.08**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Simon A. Levin	0.03	Yes
Naomi E. Leonard	0.63	
FTE Equivalent:	**0.66**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME   PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Research Accomplishments: Overview

This is the final report for this project, which has produced more than 50 publications on how consensus is achieved in large groups of independent agents, across taxonomic groups, from bacteria to humans. Individual reports for the various years are attached as appendices. We have studied, theoretically and empirically, the high degree of coordinated movements in many animal populations, and derived general principles underlying collective behavior. We have focused on scaling from individual interactions to collective behavior, and back, studying the role of communication topologies, and conflicts between individual actions and collective optimization. We feel that there is much to learn from animal groups more generally in how groups can coordinate decision-making.

In this project, we studied group decision-making in the face of conflicting information, and in particular the mechanisms by which collective behaviors emerge in nature. Of central interest is the degree to which collective optimization can be approximated in situations where individuals operate for individual benefit rather than group success. Mathematical and computational models are central to our investigations. In the early phases of this work, we studied how a group may be susceptible to manipulation by a strongly opinionated, or extremist, minority. Later work has explored this in greater detail, and the latest report below explores this in depth.

We also examined the dynamics of decision-making among finite alternatives in large networked groups using the replicator-mutator equations from evolutionary dynamics. Details may be found in the individual annual reports.

In the next phase, we studied information transfer and processing within groups, and the size and nature of the network from which individuals derive information. Again, this involved integration of empirical and theoretical studies on a number of groups. We also focused on the speed-accuracy tradeoff in gathering information, and on how individuals effectively mine environments for information. Thus we explored the integration of individual and social information, how this emerges in animal groups, and how it can inform optimal strategies of individual and collective search.

In the final phase, reported in the pages that follow, these various perspectives are integrated into coherent overall descriptions and theories.

Research Accomplishments: Final Period

1. Collective Foraging in Deep-Diving Whales (Matthieu Barbier)

Barbier developed a model of whale collective foraging: Agent-Based simulations and analytical tools have been used to study the importance of sonar directionality and organized motion in maximizing the detection and harvesting of prey in a fast-changing environment. An article in collaboration with postdoctoral researcher Frants Jensen, connecting this work to his empirical work on pilot whales and to the problem of the evolution of sonar directionality in various species is in progress.

2. The Evolution of Distributed Sensing and Collective Computation in Animal Populations (George Hagstrom, Andrew Hein, Sarah Rosenthal, Andrew Berdahl, Colin Torney, and Iain Couzin)

The mechanism by which social interactions among organisms result in coordinated and dynamic collective motion has been subject to extensive exploration in recent years. While collective motion occurs at a macroscopic level, it is driven by real-time microscopic level movement decisions made by individuals. These individual movement rules can lead to rapid transitions in group properties, reminiscent of phase transitions in physical systems. Importantly, the relationship between such pattern formation and the evolutionary drivers of collective behavior are poorly understood. It is unclear what decision rules lead to efficient collective behavior, and precisely how such rules could evolve through natural selection on individual behavior. We have investigated these phenomena with a simple model of social decision-making, based on experimental studies of schooling fish, in which agents search their environment for a resource using a combination of social and environmental information. We developed high performance numerical simulations and theoretical calculations to facilitate both the discovery of the parameters of the model that yield optimal group performance, as well evolutionary simulations to study the rules that emerge when each agent is rewarded based on its individual performance.

The numerical study revealed that evolved populations have the emergent ability to sense and climb dynamic resource gradients. This occurs even though individuals have no direct knowledge of the number, location, or size of the resource patches. The agents are able to achieve this when the parameters of the model permit the existence of two distinct stable states, a dense 'liquid' state and a dilute 'gas' state, and when the population can undergo a transition between states near the boundary of a resource path. Density differences between the two states allow agents to determine the location of resource patches from afar, making no use of gradient information. This study is the first we are aware of that shows that natural selection acting on selfish individuals can lead to groups with effective collective computation capabilities.

To support our numerical simulations, we developed a continuum description of the movements of the agents. We adapted

closure techniques used in fluid dynamics and other branches of physics to the topological interaction laws obeyed by agents in our simulation, and derived an advection-diffusion equation for the density of agents. This enabled us to find a mathematical formula for the onset of phase transitions between the dense and dilute states, which helped us verify the observation that evolved populations took advantage of phase transitions to locate and exploit research patches. We were able to model this exploitation process and demonstrate that social agents are able to colonize patches at an exponential rate, while asocial agents are only able to colonize them at a linear rate. The principles gleaned from this work will improve understanding of optimization of behavior in multi-agent systems and have the potential to inform design of control protocols for autonomous vehicles and optimization routines to be used in online optimization tasks. A manuscript from this work is complete and we plan to submit it to the journal eLIFE.

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One of the fundamental problems in ecological systems is to understand how interactions on small scales lead to macroscopic dynamics on the large scales. Large scale patterns that result from the collective behavior of biological organisms support consumers and predators in both terrestrial and marine food webs, as well as enabling interspecies interactions such as reproduction. Eulerian models describe aggregations of animals in terms of local variables such as population densities and velocities, and these models have been used to understand the results of collective interactions of all types of physical objects, from molecules to animals. Early efforts to model collective behavior were based on metric (distance) based interaction rules that were more inspired by ease of use than biological relevance. Indeed, in the past few years scientists have realized that the actual interaction laws between agents cannot usually be described using metric interactions, and it has been hypothesized that other rules are more important.

We have been working to understand the implications of a topological interaction law (one in which a biological agents interacts with nearest neighbors) on collective behavior. Topological interactions have been suggested to be more realistic than metric ones, and there is experimental evidence that they describe starling flocks and other important model organisms. It has also been suggested that the topological interaction law is important for the robustness of collective behavior and that it facilitates easy collective decision-making. We have derived Eulerian models that arise from an individual based model with a topological interaction law, including a kinetic description and hierarchy of fluid equations. We have focused on analyzing advection-diffusion equations resulting from closures of hierarchies of equations. These efforts have shown a number of different things: some common features of metric models, such as collapse in non H-stable regimes, do not occur in topological models, and the effective interaction radius is dependent on the local density. We have studied both local and global properties of equilibria of these advection-diffusion equations, deriving criteria for both linear stability/instability and conditions for global attractiveness of the homogeneous equilibrium state. This work has been coupled with numerical studies of the corresponding individual based models, both to verify the accuracy of the closure scheme and to investigate important high-level properties, such as group size distributions and group transition graphs.

4. Physical Limits on Bacterial Navigation in Dynamic Environments (Andrew Hein, Simon Levin)

Andrew Hein led a project in which we (Hein, Douglas R. Brumley, Francesco Carrara, Roman Stocker, and Simon A. Levin) developed mathematical tools to model bacterial navigation in complex environments. Many biological and artificial sensory systems have limited accuracy; the physics of environmental cues create noise that result in a lower bound on the minimum signal a sensory system can resolve. We showed that there is a lower bound on the chemical signals that bacterial cells can measure, and that this lower bound can be used to make predictions about how bacteria navigate noisy, dynamic environments. The mathematical tools we have developed are general and apply to both biological and artificial systems. We have submitted a manuscript resulting from this study to Physical Review Letters. We are continuing to develop this theoretical framework and working on a second manuscript.

5. Decision-making Under Uncertainty (Naomi Leonard)

In Srivastava, Reverdy, and Leonard (Proc. Conf. Decision and Control, December 2014), we have extended our work on modeling and analysis of individual decision-making under uncertainty in foraging to environments that are abruptly changing due to the arrival of unknown spatial events. In our earlier work (Reverdy et al., Proc. IEEE, 2014), we presented a formal model of Bayesian inference and decision-making in explore-exploit tasks using the context of multi-armed bandit (MAB) problems, where the decision-maker must choose among multiple options with uncertain (Gaussian) rewards with the goal of maximizing accumulated reward. We proved that our upper credible limit (UCL) algorithm achieves logarithmic cumulative expected regret, which is optimal performance for uninformative priors, and we showed how good priors and good assumptions on the correlation structure among arms can greatly enhance decision-making performance, even over short time horizons.

In the new work, we studied the exploration-exploitation tradeoff in MAB problems with change points. In such problems, the mean rewards from arms are not stationary, and may abruptly change to an unknown value at some unknown time. We assume that the order of the number of possible changes within time T is known. The algorithm we propose adapts the UCL algorithm to include a sliding window where only observations in this recent time-window are used to estimate mean rewards

and select arms. The width of the time-window can be chosen to achieve provably efficient performance. We also extend the algorithm to restrict the number of transitions among arms by incorporating a block allocation strategy.

In Reverdy and Leonard (Proc. Conf. Decision and Control, December 2014), we have proposed a satisficing objective for the MAB problem, where the objective is to achieve performance above a given threshold. This is a relaxation of the maximizing objective and allows for less risky decision-making in the face of uncertainty. This is evident in the algorithm we derive. We find a bound performance for this algorithm.

6. Coordination and Communication (Couzin)

Coordination among social animals requires rapid and efficient transfer of information among individuals, which may depend crucially on the underlying structure of the communication network. Establishing the decision-making circuits and networks that give rise to individual behavior has been a central goal of neuroscience. However, the analogous problem of determining the structure of the communication network among organisms that gives rise to coordinated collective behavior, such as is exhibited by schooling fish and flocking birds, has remained almost entirely neglected. We studied collective evasion maneuvers, manifested through rapid waves, or cascades, of behavioral change (a ubiquitous behavior among taxa) in schooling fish (Notemigonus crysoleucas). We automatically tracked the positions and body postures, calculated visual fields of all individuals in schools of ~150 fish, and employed statistical and machine-learning methodologies to establish how these organisms map complex, high-dimensional, sensory input to a relatively low-dimensional behavioral output (escape response) during collective evasion. We found that individuals use simple, robust measures to assess behavioral changes in neighbors, and that the resulting networks by which behavior propagates throughout groups are complex, being weighted, directed, and heterogeneous. By studying these interaction networks, we revealed the (complex, fractional) nature of social contagion and established that, in contrast to the conventional view of spreading processes that individuals with relatively few, but strongly connected, neighbors are both most socially influential and most susceptible to social influence. Furthermore, we demonstrated that we can predict complex cascades of behavioral change at their moment of initiation, before they actually occur. Consequently, despite the intrinsic stochasticity of individual behavior, establishing the hidden communication networks in large self-organized groups facilitates a quantitative understanding of behavioral contagion (Rosenthal et al., 2015).

Again considering the network of interactions among organisms we analyzed high temporal and spatial resolution global positioning system (GPS) data of a study of collective motion in baboons (Strandburg-Peshkin et al., 2015). In this study, conducted under natural field conditions in Kenya, we obtained the positions of almost all adults in a wild troop, every second, for approximately three weeks. Baboons are highly social organisms and maintained a high degree of cohesion, thus making movement decisions collectively throughout this period (such as when, and where to move). In contrast to the fish schools studied in Rosenthal et al., 2015, baboons are famous for living in complex, socially-stratified societies with a prominent, linear dominance hierarchy. Determining how collective decision-making operates in species where long-term social bonds and dominance hierarchies introduce asymmetries in individual influence remains a core challenge for understanding the evolution of social complexity, and could inform engineered systems. Because troops are heterogeneous and members differ significantly in both their needs and capabilities, conflicts of interest over movement decisions are inevitable.

We developed an automated procedure for extracting movement 'initiation attempts' based on the relative movements of pairs of individuals. Using this procedure, we extracted sequences of movements in which one individual moved away from another, and was either followed (defined as a "pull") or was not followed and subsequently returned (defined as an "anchor"). Multiple individuals can attempt to initiate movement at the same time, and furthermore they can do so in different directions. Firstly we found that neither sex nor dominance status played a role in whether individuals were followed, and thus that collective movement decisions in baboons result from a shared, democratic process. Secondly, theoretical studies of collective decision-making predict that when two subsets of individuals have conflicting directional preferences, two movement regimes will emerge: If the difference between preferred directions (angle of disagreement) is relatively small, individuals in groups are expected to "compromise" by moving in the average of these proposed directions. However, above a critical angle, individuals "choose" adopting one travel direction or the other (Couzin et al., 2005; see Figure 1, A). Consistent with this theory, baboon followers clearly exhibited these two regimes. In the simplest case of two concurrent initiators, the fine-scale movements of baboons demonstrated that followers compromised (exhibit directional averaging) when the angle of disagreement was small, but when angles exceeded approximately 90 degrees, followers consistently chose one direction or the other (Figure 1 B).

When initiators propose strongly conflicting directions, how do followers choose which direction to move in? As predicted by Couzin et al., 2005, we found that when choosing between competing groups of initiators, baboons employ a simple majority rule; they are more likely to follow the subgroup containing the greatest number of initiators. As the asymmetry in initiator group size increases, individuals become more and more likely to follow the majority (theoretical predictions shown in Figure 1C, and experimental data from wild baboons in Figure 1D).

Please see .PDF copy of paper provided as attachment.

Figure 1. Comparison of theoretical predictions (A and C) and experimental data (B and D) for the direction taken by individuals as a function of the angular difference between potential leaders for conditions when there are an equal number in each opposing subset (A and B) and when the lower subset (set to 0 degrees) is in the majority (C and D). Modified from Couzin et al., 2005 (A and C) and Strandburg-Peshkin et al., 2015 (B and D).

Bibliography

Published Papers

Bazazi, S., Bartumeus, F., Hale, J.J., Holmin, A.J., and Couzin, I.D. 2012. Intermittent motion in desert locusts: Behavioral complexity in simple environments. PLoS Computational Biology 8(5): e1002498.

Berdahl, A., Torney, C.J., Ioannou, C.C., Faria, J., and Couzin, I.D. 2013. Emergent sensing of complex environments by mobile animal groups. Science 339(6119): 574-576.

Berdahl, A., Torney, C.J., Schertzer, E., and Levin, S.A. 2015. On the evolutionary interplay between dispersal and local adaptation in heterogeneous environments. Evolution 69(6): 1390-405.

Berdahl, A., Westley, P.A.H., Couzin, I.D., Levin, S.A., and Quinn, T.P. 2014. A collective navigation hypothesis for homeward migration in anadromous salmonids. Fish and Fisheries: DOI: 10.1111/faf.12084.

Gallup, A.C., Chong, A., and Couzin, I.D. 2012. The directional flow of visual information transfer between pedestrians. Biology Letters 8(4): 520-522.

Gallup, A.C., Chong, A., Kacelnik, A., Krebs, J.R., and Couzin, I.D. 2014. The influence of emotional facial expressions on gaze-following in grouped and solitary pedestrians. Scientific Reports 4: 5794.

Gallup, A.C., Hale, J.J., Garnier, S., Sumpter, D.J.T., Kacelnik, A., Krebs, J., and Couzin, I.D. 2012. Visual attention and the acquisition of information in human crowds. PNAS 109(19): 7245-7250.

Garnier, S., Murphy, T., Lutz, M., Hurme, E., Leblanc, S., and Couzin, I.D. 2013. Stability and responsiveness in a self-organizing living architecture. PLoS Computational Biology 9(3): e1002984.

Giuggiolo, L., Potts, J.R., Rubenstein, D.I., and Levin, S.A. 2013. Stigmergy, collective actions, and animal social spacing. PNAS 110(42): 16904-16909.

Guttal, V., Romanczuk, P., Simpson, S.J., Sword, G.A., and Couzin, I.D. 2012. Cannibalism can drive the evolution of behavioral phase polyphenism in locusts. Ecology Letters 15: 1158-1166.

Handegard, N.O., Leblanc, S., Boswell, K., Tjostheim, D., and Couzin, I.D. 2012. The dynamics of coordinated group hunting and collective information-transfer among schooling prey. Current Biology 22(13): 1213-1217.

Hofmann, H.A., Blumstein, D.T., Couzin, I.D., Earley, R.L., Hayes, L.D., Hurd, P.L., Lacey, E.A., Solomon, N.G., Taborsky, M., Young, I.J., and Rubenstein, D.R. 2014. An evolutionary framework for studying mechanisms of social behavior. Trends in Ecology and Evolution 29(10): 581-589.

Ioannou, C.C., Guttal, V., and Couzin, I.D. 2012. Predatory fish select for coordinated collective motion in virtual prey. Science 337(6099): 1212-1215.

Ioannou, C.C., Singh, M., and Couzin, I.D. 2015. Potential leaders trade off goal-oriented and socially oriented behavior in mobile animal groups. The American Naturalist 186(2): 284-293.

Kao, A.B. and Couzin, I.D. 2014. Decision accuracy in complex environments is often maximized by small group sizes. Proceedings of the Royal Society of London Series B 281(1784): 0133305.

Kao, A., Miller, N., Torney, C., Hartnett, A., and Couzin, I.D. 2014. Collective learning and optimal consensus in social animal groups. PLoS Computational Biology 10(8): e1003762.

Kolpas, A., Busch, M., Li, H., Couzin, I.D., Petzold, L., and Moehlis, J. 2013. How the spatial position of individuals affects their influence on swarms: A numerical comparison of two popular swarm dynamics models. PLoS ONE 8(3): e58525.

Leonard, N.E., Shen, T., Nabet, B., Scardovi, L., Couzin, I.D., and Levin, S.A. 2012. Decision versus compromise for animal groups in motion. PNAS 109: 227-232.

Leonard, N.E. and Olshevsky, A. 2013. Cooperative learning in multi-agent systems from intermittent measurements. Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy: 7492-7497.

Leonard, N.E. and Olshevsky, A. 2015. Cooperative learning in multi-agent systems from intermittent measurements. SIAM Journal on Control and Optimization 53(1): 1-29.

Leonard, N.E. 2013. Multi-agent system dynamics: Bifurcation and behavior of animal groups. Proceedings of the 9th IFAC Symposium on Nonlinear Control Systems, Toulouse, France 9(1): 307-217.

Leonard, N.E. 2014. Multi-agent system dynamics: Bifurcation and behavior of animal groups. IFAC Annual Reviews in Control 38(2): 171-183.

Lopez, U., Gautrais, J., Couzin, I.D., and Theraulaz, G. 2012. From behavioral analyses tomodels of collective motion in fish schools. Interface Focus: DOI: 10.1098/rfs.2012.0033.

Miller, N., Garnier, S., and Couzin, I.D. 2013. Both information and social cohesion determine collective decisions in animal groups. PNAS 110(13): 5263-5268.

Mishra, S., Tunstrom, K., Couzin, I.D., and Huepe, C. 2012. Collective dynamics of self-propelled particles with variable speed. Physical Review E 86: 011901.

Pais, D., Caicedo-Nunez, C.H., and Leonard, NE. 2012. Hopf bifurcations and limit cycles in evolutionary network dynamics. SIAM Journal on Applied Dynamical Systems 11(4): 1754-1884.

Pais, D. and N.E. Leonard. 2014. Adaptive network dynamics and evolution of leadership in collective migration. Physica D: Nonlinear Phenomena 267: 81-93.

Perez-Escudero, A., Miller, N., Hartnett, A.T., Garnier, S., Couzin, I.D., and Polavieja, G. 2013. Estimation models describe well collective decisions among three options. PNAS 110(37): E3466-E3467.

Reverdy, P., Srivastava, V., and Leonard, N.E. 2014. Modeling human decision-making in generalized Gaussian multi-armed bandits. Proceedings of the IEEE 102(4): 544-571.

Reverdy, P., Srivastava, V., and Leonard, N.E. 2014. Algorithmic models of human decision making in Gaussian multi-armed bandit problems. Proceedings of the 2014 European Control Conference, Strasbourg, France: 2210-2215. Won award for Best Student Paper.

Reverdy, P. and Leonard, N.E. 2014. Satisficing in Gaussian bandit problems. Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014: 5718-5723.

Rosenthal, S.B., Twomey, C.R., Hartnett, A.T., Wu, H.S., and Couzin, I.D. 2015. Revealing the hidden networks of interaction in mobile animal groups allows prediction of complex behavioral contagion. PNAS 112(15): 4690-4695.

Scott, W. and N.E. Leonard. 2014. Dynamics of pursuit and evasion in a heterogeneous herd. Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014: 2920-2925.

Shaw, A.K. and Couzin, I.D. 2013. Migration or residency? The evolution of movement behavior and information usage in seasonal environments. The American Naturalist 181(1): 114-124.

Srivastava, V. and Leonard, N.E. 2014. Collective decision-making in ideal networks: The speed-accuracy tradeoff. IEEE Transactions on Control of Network Systems 1(1): 121-132.

Srivastava, V. and Leonard, N.E. 2013. On the speed-accuracy tradeoff in collective decision making. Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy: 1880-1885.

Srivastava, V., Reverdy, P., and Leonard, N.E. 2013. Optimal foraging and multi-armed bandits. Proceedings of the 51st Allerton Conference on Communication, Control, and Computing, Monticello, IL, October 2013.

Srivastava, V., Reverdy, P., and N.E. Leonard. 2014. Surveillance in an abruptly changing world via multiarmed bandits.

Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014: 692-697.

Strandburg-Peshkin, A., Farine, D.R., Couzin, I.D., and Crofoot, M.C. 2015. Shared decision-making drives collective movement in wild baboons. Science 348(6241): 1358-1361.

Strandburg-Peshkin, A., Twomey, C.R., Bode, N.W., Kao, A.B., Katz, Y., Ioannou, C.C., Rosenthal, B., Torney, C.J., Wu, H., Levin, S.A., and Couzin, I.D. 2013. Visual sensory networks and effective information transfer in animal groups. Current Biology 23(17): R709-711.

Swain, D.T., Couzin, I.D., and Leonard, N.E. 2015. Coordinated speed oscillations in schooling killifish enrich social communication. Journal of Nonlinear Science: DOI 10.1007/s00332-015-9263-8.

Torney, C.J., Levin, S.A., and Couzin, I.D. 2013. Decision accuracy and the role of spatial interaction in opinion dynamics. Journal of Statistical Physics 151: 203-217.

Torney, C.J., Lorenzi, T., Couzin, I.D, and Levin, S.A. 2015. Information processing and the evolution of unresponsiveness in collective systems. Journal of the Royal Society Interface 12(103): 20140893.

Tunstrom, K., Katz, Y., Ioannou, C.C., Huepe, C., Lutz, M., and Couzin, I.D. 2013. Collective states, multistability and transitional behavior in animal groups. PLoS Computational Biology 9(2): e1002915.

Young, G.F., Scardovi, L., Cavagna, A., Giardina, I., and Leonard, N.E. 2013. Starling flock networks manage uncertainty in consensus at low cost. PLoS Computational Biology 9(1): e1002894.

Manuscripts

Fitch, K.E. and Leonard, N.E. 2014. Joint centrality distinguishes optimal leaders in noisy networks. Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy, December 10-13, 2013. arXiv:1407.1569v1. Submitted.

Hartnett, A.T., Schertzer, E., Levin, S.A., and Couzin, I.D. 2015. Heterogeneous preference and local nonlinearity in consensus decision-making. Physical Review Letters. Submitted.

Hein, A.M., Rosenthal, S.B., Hagstrom, G.I., Berdahl, A., and Couzin, I.D. 2015. The evolution of distributed sensing and collective computation in animal populations. PNAS. Submitted.

Hein, A.M., Levin, S.A., Brumley, D.R., Carrara, F., and Stocker, R. 2015. Physical limits on bacterial navigation in dynamic environments. Physical Review Letters. Submitted.

Poulakakis, I., Scardovi, L., and Leonard, N.E. 2016. Node certainty in collective decision making. Proceedings of the 51st IEEE Conference on Decision and Control, Maui, HI: 4648-4653. Submitted 2012. Accepted for publication, to appear March 2016.

Poulakakis, I., Young, G.F., Scardovi, L., and N.E. Leonard. 2016. Information centrality and ordering of nodes for accuracy in noisy decision-making networks. IEEE Transactions on Automatic Control. Submitted 2012. Accepted for publication, to appear March 2016.

Young, G.F., Scardovi, L., and Leonard, N.E. A new notion of effective resistance for directed graphs – Part I: Definition and properties. IEEE Transactions on Automatic Control.   arXiv:1310.5163v2 [math.OC]. Accepted.

Young, G.F., Scardovi, L., and Leonard, N.E. A new notion of effective resistance for directed graphs – Part II: Computing resistances. IEEE Transactions on Automatic Control. arXiv:1310.5168v2 [math.OC]. Accepted.

Technology Transfer

Coordination and Collective Decision Making
W911NF-11-1-0385

Research Accomplishments: Overview

This is the final report for this project, which has produced more than 50 publications on how consensus is achieved in large groups of independent agents, across taxonomic groups, from bacteria to humans. Individual reports for the various years are attached as appendices. We have studied, theoretically and empirically, the high degree of coordinated movements in many animal populations, and derived general principles underlying collective behavior. We have focused on scaling from individual interactions to collective behavior, and back, studying the role of communication topologies, and conflicts between individual actions and collective optimization. We feel that there is much to learn from animal groups more generally in how groups can coordinate decision-making.

In this project, we studied group decision-making in the face of conflicting information, and in particular the mechanisms by which collective behaviors emerge in nature. Of central interest is the degree to which collective optimization can be approximated in situations where individuals operate for individual benefit rather than group success. Mathematical and computational models are central to our investigations. In the early phases of this work, we studied how a group may be susceptible to manipulation by a strongly opinionated, or extremist, minority. Later work has explored this in greater detail, and the latest report below explores this in depth.

We also examined the dynamics of decision-making among finite alternatives in large networked groups using the replicator-mutator equations from evolutionary dynamics. Details may be found in the individual annual reports.

In the next phase, we studied information transfer and processing within groups, and the size and nature of the network from which individuals derive information. Again, this involved integration of empirical and theoretical studies on a number of groups. We also focused on the speed-accuracy tradeoff in gathering information, and on how individuals effectively mine environments for information. Thus we explored the integration of individual and social information, how this emerges in animal groups, and how it can inform optimal strategies of individual and collective search.

In the final phase, reported in the pages that follow, these various perspectives are integrated into coherent overall descriptions and theories.

Research Accomplishments: Final Period

1. Collective Foraging in Deep-Diving Whales (Matthieu Barbier)
Barbier developed a model of whale collective foraging: Agent-Based simulations and analytical tools have been used to study the importance of sonar directionality and organized motion in maximizing the detection and harvesting of prey in a fast-changing environment. An article in collaboration with postdoctoral researcher Frants Jensen, connecting this work to his empirical work on pilot whales and to the problem of the evolution of sonar directionality in various species is in progress.

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5. Decision-making under Uncertainty (Naomi Leonard)

In Srivastava, Reverdy, and Leonard (Proc. Conf. Decision and Control, December 2014), we have extended our work on modeling and analysis of individual decision-making under uncertainty in foraging to environments that are abruptly changing due to the arrival of unknown spatial events. In our earlier work (Reverdy et al., Proc. IEEE, 2014), we presented a formal model of Bayesian inference and decision-making in explore-exploit tasks using the context of multi-armed bandit (MAB) problems, where the decision-maker must choose among multiple options with uncertain (Gaussian) rewards with the goal of maximizing accumulated reward. We proved that our upper credible limit (UCL) algorithm achieves logarithmic cumulative expected regret, which is optimal performance for uninformative priors, and we showed how good priors and good assumptions on the correlation structure among arms can greatly enhance decision-making performance, even over short time horizons.

In the new work, we studied the exploration-exploitation tradeoff in MAB problems with change points. In such problems, the mean rewards from arms are not stationary, and may abruptly change to an unknown value at some unknown time. We assume that the order of the number of possible changes within time T is known. The algorithm we propose adapts the UCL algorithm to include a sliding window where only observations in this recent time-window are used to estimate mean rewards and select arms. The width of the time-window can be chosen to achieve provably efficient performance. We also extend the algorithm to restrict the number of transitions among arms by incorporating a block allocation strategy.

In Reverdy and Leonard (Proc. Conf. Decision and Control, December 2014), we have proposed a satisficing objective for the MAB problem, where the objective is to achieve performance above a given threshold. This is a relaxation of the maximizing objective and allows for less risky decision-making in the face of uncertainty. This is evident in the algorithm we derive. We find a bound performance for this algorithm.

6. Coordination and Communication (Couzin)

Coordination among social animals requires rapid and efficient transfer of information among individuals, which may depend crucially on the underlying structure of the communication network. Establishing the

decision-making circuits and networks that give rise to individual behavior has been a central goal of neuroscience. However, the analogous problem of determining the structure of the communication network among organisms that gives rise to coordinated collective behavior, such as is exhibited by schooling fish and flocking birds, has remained almost entirely neglected. We studied collective evasion maneuvers, manifested through rapid waves, or cascades, of behavioral change (a ubiquitous behavior among taxa) in schooling fish (*Notemigonus crysoleucas*). We automatically tracked the positions and body postures, calculated visual fields of all individuals in schools of ∼150 fish, and employed statistical and machine-learning methodologies to establish how these organisms map complex, high-dimensional, sensory input to a relatively low-dimensional behavioral output (escape response) during collective evasion. We found that individuals use simple, robust measures to assess behavioral changes in neighbors, and that the resulting networks by which behavior propagates throughout groups are complex, being weighted, directed, and heterogeneous. By studying these interaction networks, we revealed the (complex, fractional) nature of social contagion and established that, in contrast to the conventional view of spreading processes that individuals with relatively few, but strongly connected, neighbors are both most socially influential and most susceptible to social influence. Furthermore, we demonstrated that we can predict complex cascades of behavioral change at their moment of initiation, before they actually occur. Consequently, despite the intrinsic stochasticity of individual behavior, establishing the hidden communication networks in large self-organized groups facilitates a quantitative understanding of behavioral contagion (Rosenthal et al., 2015).

Again considering the network of interactions among organisms we analyzed high temporal and spatial resolution global positioning system (GPS) data of a study of collective motion in baboons (Strandburg-Peshkin et al., 2015). In this study, conducted under natural field conditions in Kenya, we obtained the positions of almost all adults in a wild troop, every second, for approximately three weeks. Baboons are highly social organisms and maintained a high degree of cohesion, thus making movement decisions collectively throughout this period (such as when, and where to move). In contrast to the fish schools studied in Rosenthal et al., 2015, baboons are famous for living in complex, socially-stratified societies with a prominent, linear dominance hierarchy. Determining how collective decision-making operates in species where long-term social bonds and dominance hierarchies introduce asymmetries in individual influence remains a core challenge for understanding the evolution of social complexity, and could inform engineered systems. Because troops are heterogeneous and members differ significantly in both their needs and capabilities, conflicts of interest over movement decisions are inevitable.

We developed an automated procedure for extracting movement 'initiation attempts' based on the relative movements of pairs of individuals. Using this procedure, we extracted sequences of movements in which one individual moved away from another, and was either followed (defined as a "pull") or was not followed and subsequently returned (defined as an "anchor"). Multiple individuals can attempt to initiate movement at the same time, and furthermore they can do so in different directions. Firstly we found that neither sex nor dominance status played a role in whether individuals were followed, and thus that collective movement decisions in baboons result from a shared, democratic process. Secondly, theoretical studies of collective decision-making predict that when two subsets of individuals have conflicting directional preferences, two movement regimes will emerge: If the difference between preferred directions (angle of disagreement) is relatively small, individuals in groups are expected to "compromise" by moving in the average of these proposed directions. However, above a critical angle, individuals "choose" adopting one travel direction or the other (Couzin et al., 2005; see Figure 1, A). Consistent with this theory, baboon followers clearly exhibited these two regimes. In the simplest case of two concurrent initiators, the fine-scale movements of baboons demonstrated that followers compromised (exhibit directional averaging) when the angle of disagreement was small, but when angles exceeded approximately 90 degrees, followers consistently chose one direction or the other (Figure 1 B).

When initiators propose strongly conflicting directions, how do followers choose which direction to move in? As predicted by Couzin et al., 2005, we found that when choosing between competing groups of

initiators, baboons employ a simple majority rule; they are more likely to follow the subgroup containing the greatest number of initiators. As the asymmetry in initiator group size increases, individuals become more and more likely to follow the majority (theoretical predictions shown in Figure 1C, and experimental data from wild baboons in Figure 1D).
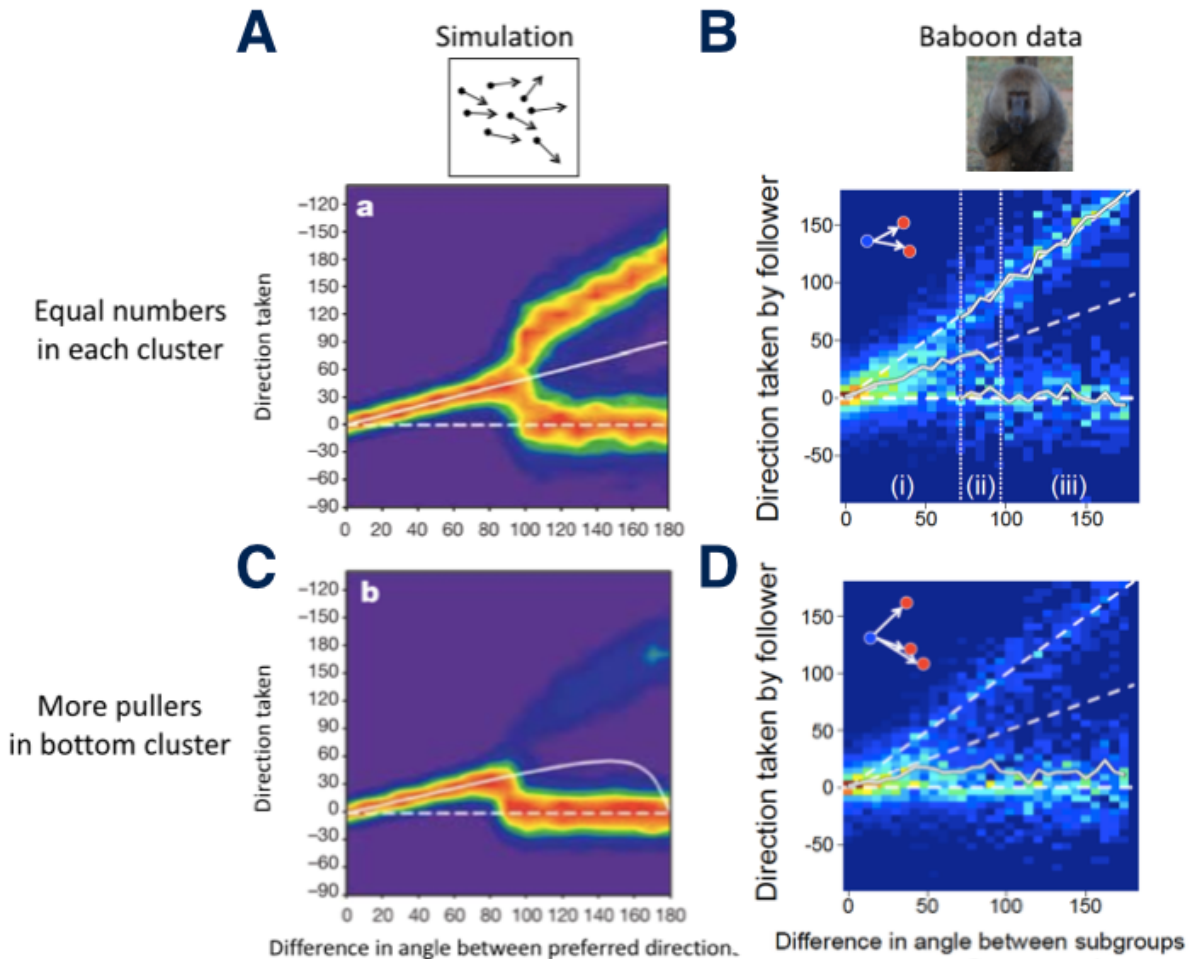

Figure 1. Comparison of theoretical predictions (A and C) and experimental data (B and D) for the direction taken by individuals as a function of the angular difference between potential leaders for conditions when there are an equal number in each opposing subset (A and B) and when the lower subset (set to 0 degrees) is in the majority (C and D). Modified from Couzin et al., 2005 (A and C) and Strandburg-Peshkin et al., 2015 (B and D).

Bibliography

Published Papers

Bazazi, S., Bartumeus, F., Hale, J.J., Holmin, A.J., and Couzin, I.D. 2012. Intermittent motion in desert locusts: Behavioral complexity in simple environments. *PLoS Computational Biology* 8(5): e1002498.

Berdahl, A., Torney, C.J., Ioannou, C.C., Faria, J., and Couzin, I.D. 2013. Emergent sensing of complex environments by mobile animal groups. *Science* 339(6119): 574-576.

Berdahl, A., Torney, C.J., Schertzer, E., and Levin, S.A. 2015. On the evolutionary interplay between dispersal and local adaptation in heterogeneous environments. *Evolution* 69(6): 1390-405.

Berdahl, A., Westley, P.A.H., Couzin, I.D., Levin, S.A., and Quinn, T.P. 2014. A collective navigation hypothesis for homeward migration in anadromous salmonids. *Fish and Fisheries:*
DOI: 10.1111/faf.12084.

Gallup, A.C., Chong, A., and Couzin, I.D. 2012. The directional flow of visual information transfer between pedestrians. *Biology Letters* 8(4): 520-522.

Gallup, A.C., Chong, A., Kacelnik, A., Krebs, J.R., and Couzin, I.D. 2014. The influence of emotional facial expressions on gaze-following in grouped and solitary pedestrians. *Scientific Reports* 4: 5794.

Gallup, A.C., Hale, J.J., Garnier, S., Sumpter, D.J.T., Kacelnik, A., Krebs, J., and Couzin, I.D. 2012. Visual attention and the acquisition of information in human crowds. *PNAS* 109(19): 7245-7250.

Garnier, S., Murphy, T., Lutz, M., Hurme, E., Leblanc, S., and Couzin, I.D. 2013. Stability and responsiveness in a self-organizing living architecture. *PLoS Computational Biology* 9(3): e1002984.

Giuggiolo, L., Potts, J.R., Rubenstein, D.I., and Levin, S.A. 2013. Stigmergy, collective actions, and animal social spacing. *PNAS* 110(42): 16904-16909.

Guttal, V., Romanczuk, P., Simpson, S.J., Sword, G.A., and Couzin, I.D. 2012. Cannibalism can drive the evolution of behavioral phase polyphenism in locusts. *Ecology Letters* 15: 1158-1166.

Handegard, N.O., Leblanc, S., Boswell, K., Tjostheim, D., and Couzin, I.D. 2012. The dynamics of coordinated group hunting and collective information-transfer among schooling prey. *Current Biology* 22(13): 1213-1217.

Hofmann, H.A., Blumstein, D.T., Couzin, I.D., Earley, R.L., Hayes, L.D., Hurd, P.L., Lacey, E.A., Solomon, N.G., Taborsky, M., Young, I.J., and Rubenstein, D.R. 2014. An evolutionary framework for studying mechanisms of social behavior. *Trends in Ecology and Evolution* 29(10): 581-589.

Ioannou, C.C., Guttal, V., and Couzin, I.D. 2012. Predatory fish select for coordinated collective motion in virtual prey. *Science* 337(6099): 1212-1215.

Ioannou, C.C., Singh, M., and Couzin, I.D. 2015. Potential leaders trade off goal-oriented and socially oriented behavior in mobile animal groups. *The American Naturalist* 186(2): 284-293.

Kao, A.B. and Couzin, I.D. 2014. Decision accuracy in complex environments is often maximized by small group sizes. *Proceedings of the Royal Society of London Series B* 281(1784): 0133305.

Kao, A., Miller, N., Torney, C., Hartnett, A., and Couzin, I.D. 2014. Collective learning and optimal consensus in social animal groups. *PLoS Computational Biology* 10(8): e1003762.

Kolpas, A., Busch, M., Li, H., Couzin, I.D., Petzold, L., and Moehlis, J. 2013. How the spatial position of individuals affects their influence on swarms: A numerical comparison of two popular swarm dynamics models. *PLoS ONE* 8(3): e58525.

Leonard, N.E., Shen, T., Nabet, B., Scardovi, L., Couzin, I.D., and Levin, S.A. 2012. Decision versus compromise for animal groups in motion. *PNAS* 109: 227-232.

Leonard, N.E. and Olshevsky, A. 2013. Cooperative learning in multi-agent systems from intermittent measurements. *Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy:* 7492-7497.

Leonard, N.E. and Olshevsky, A. 2015. Cooperative learning in multi-agent systems from intermittent measurements. *SIAM Journal on Control and Optimization* 53(1): 1-29.

Leonard, N.E. 2013. Multi-agent system dynamics: Bifurcation and behavior of animal groups. *Proceedings of the 9th IFAC Symposium on Nonlinear Control Systems,* Toulouse, France 9(1): 307-217.

Leonard, N.E. 2014. Multi-agent system dynamics: Bifurcation and behavior of animal groups. *IFAC Annual Reviews in Control* 38(2): 171-183.

Lopez, U., Gautrais, J., Couzin, I.D., and Theraulaz, G. 2012. From behavioral analyses tomodels of collective motion in fish schools. *Interface Focus:* DOI: 10.1098/rfs.2012.0033.

Miller, N., Garnier, S., and Couzin, I.D. 2013. Both information and social cohesion determine collective decisions in animal groups. *PNAS* 110(13): 5263-5268.

Mishra, S., Tunstrom, K., Couzin, I.D., and Huepe, C. 2012. Collective dynamics of self-propelled particles with variable speed. *Physical Review E* 86: 011901.

Pais, D., Caicedo-Nunez, C.H., and Leonard, NE. 2012. Hopf bifurcations and limit cycles in evolutionary network dynamics. *SIAM Journal on Applied Dynamical Systems* 11(4): 1754-1884.

Pais, D. and N.E. Leonard. 2014. Adaptive network dynamics and evolution of leadership in collective migration. *Physica D: Nonlinear Phenomena* 267: 81-93.

Perez-Escudero, A., Miller, N., Hartnett, A.T., Garnier, S., Couzin, I.D., and Polavieja, G. 2013. Estimation models describe well collective decisions among three options. *PNAS* 110(37): E3466-E3467.

Reverdy, P., Srivastava, V., and Leonard, N.E. 2014. Modeling human decision-making in generalized Gaussian multi-armed bandits. *Proceedings of the IEEE* 102(4): 544-571.

Reverdy, P., Srivastava, V., and Leonard, N.E. 2014. Algorithmic models of human decision making in Gaussian multi-armed bandit problems. *Proceedings of the 2014 European Control Conference,* Strasbourg, France: 2210-2215. *Won award for Best Student Paper.*

Reverdy, P. and Leonard, N.E. 2014. Satisficing in Gaussian bandit problems. *Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014:* 5718-5723.

Rosenthal, S.B., Twomey, C.R., Hartnett, A.T., Wu, H.S., and Couzin, I.D. 2015. Revealing the hidden networks of interaction in mobile animal groups allows prediction of complex behavioral contagion. *PNAS* 112(15): 4690-4695.

Scott, W. and N.E. Leonard. 2014. Dynamics of pursuit and evasion in a heterogeneous herd. *Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014:* 2920-2925.

Shaw, A.K. and Couzin, I.D. 2013. Migration or residency? The evolution of movement behavior and information usage in seasonal environments. *The American Naturalist* 181(1): 114-124.

Srivastava, V. and Leonard, N.E. 2014. Collective decision-making in ideal networks: The speed-accuracy tradeoff. *IEEE Transactions on Control of Network Systems* 1(1): 121-132.

Srivastava, V. and Leonard, N.E. 2013. On the speed-accuracy tradeoff in collective decision making. *Proceedings of the 52nd IEEE Conference on Decision and Control, Florence, Italy:* 1880-1885.

Srivastava, V., Reverdy, P., and Leonard, N.E. 2013. Optimal foraging and multi-armed bandits. *Proceedings of the 51st Allerton Conference on Communication, Control, and Computing, Monticello, IL, October 2013.*

Srivastava, V., Reverdy, P., and N.E. Leonard. 2014. Surveillance in an abruptly changing world via multiarmed bandits. *Proceedings of the 53rd IEEE Conference on Decision and Control, Los Angeles, CA., December 15-17, 2014:* 692-697.

Strandburg-Peshkin, A., Farine, D.R., Couzin, I.D., and Crofoot, M.C. 2015. Shared decision-making drives collective movement in wild baboons. *Science* 348(6241): 1358-1361.

Strandburg-Peshkin, A., Twomey, C.R., Bode, N.W., Kao, A.B., Katz, Y., Ioannou, C.C., Rosenthal, B., Torney, C.J., Wu, H., Levin, S.A., and Couzin, I.D. 2013. Visual sensory networks and effective information transfer in animal groups. *Current Biology* 23(17): R709-711.

Swain, D.T., Couzin, I.D., and Leonard, N.E. 2015. Coordinated speed oscillations in schooling killifish enrich social communication. *Journal of Nonlinear Science:* DOI 10.1007/s00332-015-9263-8.

Torney, C.J., Levin, S.A., and Couzin, I.D. 2013. Decision accuracy and the role of spatial interaction in opinion dynamics. *Journal of Statistical Physics* 151: 203-217.

Torney, C.J., Lorenzi, T., Couzin, I.D, and Levin, S.A. 2015. Information processing and the evolution of unresponsiveness in collective systems. *Journal of the Royal Society Interface* 12(103): 20140893.

Tunstrom, K., Katz, Y., Ioannou, C.C., Huepe, C., Lutz, M., and Couzin, I.D. 2013. Collective states, multistability and transitional behavior in animal groups. *PLoS Computational Biology* 9(2): e1002915.

Young, G.F., Scardovi, L., Cavagna, A., Giardina, I., and Leonard, N.E. 2013. Starling flock networks manage uncertainty in consensus at low cost. *PLoS Computational Biology* 9(1): e1002894.

Manuscripts

Fitch, K.E. and Leonard, N.E. 2014. Joint centrality distinguishes optimal leaders in noisy networks. *Proceedings of the 52nd IEEE Conference on Decision and Control*, Florence, Italy, December 10-13, 2013. arXiv:1407.1569v1. *Submitted.*

Hartnett, A.T., Schertzer, E., Levin, S.A., and Couzin, I.D. 2015. Heterogeneous preference and local nonlinearity in consensus decision-making. *Physical Review Letters. Submitted.*

Hein, A.M., Rosenthal, S.B., Hagstrom, G.I., Berdahl, A., and Couzin, I.D. 2015. The evolution of distributed sensing and collective computation in animal populations. *PNAS. Submitted*.

Hein, A.M., Levin, S.A., Brumley, D.R., Carrara, F., and Stocker, R. 2015. Physical limits on bacterial navigation in dynamic environments. *Physical Review Letters. Submitted.*

Poulakakis, I., Scardovi, L., and Leonard, N.E. 2016. Node certainty in collective decision making. *Proceedings of the 51st IEEE Conference on Decision and Control, Maui, HI:* 4648-4653. *Submitted 2012. Accepted for publication, to appear March 2016.*

Poulakakis, I., Young, G.F., Scardovi, L., and N.E. Leonard. 2016. Information centrality and ordering of nodes for accuracy in noisy decision-making networks. *IEEE Transactions on Automatic Control. Submitted 2012. Accepted for publication, to appear March 2016.*

Young, G.F., Scardovi, L., and Leonard, N.E. A new notion of effective resistance for directed graphs – Part I: Definition and properties. *IEEE Transactions on Automatic Control.* arXiv:1310.5163v2 [math.OC]. *Accepted.*

Young, G.F., Scardovi, L., and Leonard, N.E. A new notion of effective resistance for directed graphs – Part II: Computing resistances. *IEEE Transactions on Automatic Control.* arXiv:1310.5168v2 [math.OC]. *Accepted.*